International aviation and the Paris Agreement temperature goals

David S. Lee

Manchester Metropolitan University, Faculty of Science and Engineering, School of Science and the Environment, John Dalton Building, Chester Street, Manchester M1 5GD.

Summary

Long-term goals for carbon dioxide (CO_2) emissions from total and international global aviation are considered here in the context of the Paris Agreement, which sets out a goal to hold increases in global mean surface temperature to well below 2°C above pre-industrial levels by 2100 and to pursue efforts to limit this increase to 1.5°C. In order to put this into practice, a scientifically-based 'cumulative carbon budget' approach is being taken, whereby the cumulative anthropogenic CO_2 released scales with the global mean surface temperature response, as shown by the Intergovernmental Panel on Climate Change (IPCC) and others.

For the Paris Agreement's goals to be met, large reductions in global greenhouse gas emissions are required. International aviation emissions of CO_2 (~65% of the current total from aviation) fall to the International Civil Aviation Organization (ICAO), whereas domestic emissions (~35% of the current total from aviation) come under states' Nationally Determined Contributions (NDCs). ICAO has set a 'Carbon Neutral Growth' goal (CNG2020) for international aviation emissions of CO_2 not to increase over 2020 levels, which it aims to achieve largely by offsetting.

It is shown here that even if international aviation CO_2 emissions are offset above 2020 levels, projected cumulative emissions of CO_2 from international aviation between 2016 and 2050 will consume between ~3% and 10% of the cumulative global CO_2 budget,[1] as determined by background scenarios that limit global mean temperature increases to less than 2°C, or between ~4% and 15% for the sector as a whole. For scenarios closer to 1.5°C, aviation's consumption of the CO_2 budget would be a larger fraction.

The Paris Agreement is a temperature-based target and therefore implies inclusion of *all* emissions that affect climate. Aviation has significant non-CO_2 climate impacts from oxides of nitrogen (NO_x), particle emissions, and effects on cloudiness that overall cause additional overall warming but these impacts are subject to greater scientific uncertainty than its CO_2 impacts. Examples of CO_2 emission-equivalents metrics indicate up to a doubling of aviation CO_2 equivalent emissions to account for these non-CO_2 effects.

In order to limit temperatures to less than 2°C by 2100, global CO_2 emissions will be required to go to zero around 2075; for 1.5°C scenarios, emissions will be required to go to zero around 2050. In both cases, further deeper emission cuts past the dates of zero emissions to 'negative emissions' are necessary – i.e. CO_2 removal from the atmosphere. Therefore, for 1.5°C global scenarios, any continued emissions of CO_2 from aviation using fossil fuels beyond around 2050 will be inconsistent with the Paris Agreement goals in the absence of extra measures, or alternatively, correspondingly increased negative emissions. Negative emissions technologies required to limit global mean surface temperatures are required as early as around 2035 but reliance on them to compensate for continued fossil fuel emissions from aviation would be risky. In light of this, revised goals for international aviation CO_2 emissions over and above ICAO's CNG2020 goal should be considered.

[1] The CO_2 budgets used in this paper are the CO_2 component of multi-gas pathways that also include other non-CO_2 greenhouse gas emissions such as those of nitrous oxide (N_2O) and methane (CH_4), which are recognized to contribute towards warming

1 Introduction

Aviation largely uses jet fuel ('Jet-A' kerosene) and small amounts of 'Avgas' (aviation gasoline – mostly used in small propeller engine light aircraft) (IEA, 2018). Combustion of 1 kg of kerosene results in the emission of ~3.15 kg CO_2 (IPCC, 1999). Kerosene is at present largely fossil-fuel derived, and therefore the CO_2 emitted contributes to global emissions of CO_2 and its associated global warming. So-called 'lower carbon sustainable aviation fuels' (largely biofuels) are not widely commercially available because of limited production and their current usage in aviation is largely restricted to testing and demonstration purposes (Hari et al. 2015; Chuck, 2016). Other aviation power sources, such as liquid hydrogen fuel and electric power have been discussed (e.g. Cecere et al., 2014; Gohardani et al., 2011) but have not yet been developed for the commercial fleet because of technological and infrastructural challenges, although at least one project is under active development.[2]

Emissions of total[3] aviation CO_2 are of the order 2% – 2.5% of global CO_2 emissions[4] on an annual basis (Lee et al., 2009). Total aviation kerosene usage in 2015 was 281 million tonnes[5] (Mt), according to the International Energy Agency (IEA, 2018), which equates to 885 million tonnes of CO_2. Figure 1 shows the global increase in aviation CO_2 emissions, which averaged an increase of 2.25% per year over the period 1995 to 2015. Air traffic, in terms of Revenue Passenger Kilometres (RPK)[6] increased at a greater rate than CO_2 emissions, at around 5.7% per year over the same period – the slower increase of CO_2 emissions is a result of improving fuel efficiency, from trends in aircraft size, technology improvements, and increasing load factor (Lee et al., 2009).

From Figure 1, it is clear that global air traffic has increased strongly, and its CO_2 emissions continue to increase, despite technological and operational efficiency improvements. Various scenarios of future air traffic and emissions have been formulated out to 2050 (e.g. IPCC, 1999; CONSAVE, 2005; Owen et al., 2010). The International Civil Aviation Organization (ICAO) has put forward its own traffic and emissions projections to 2050 that indicate continued growth in air traffic and emissions (Fleming and Ziegler, 2016). In this paper, the ICAO emissions projections are examined in detail along with the reductions that various policies and measures introduced by ICAO will have on international aviation CO_2 emissions. These projections are put in the context of global emissions reductions required under the Paris Agreement to limit increases in global mean surface temperature to well below 2°C by 2100, over pre-industrial levels.[7]

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[2] E-Fan X, a collaboration between Airbus, Siemens and Rolls-Royce (https://www.siemens.com/innovation/en/home/pictures-of-the-future/mobility-and-motors/the-future-of-mobility-e-fan-x.html)

[3] Total aviation comprises 'domestic' + 'international', where domestic is within a country (e.g. London to Manchester; Los Angeles to New York) and international is cross-border (e.g. London to Paris; Oslo to Amsterdam). Domestic emissions come under signatories to the United Nations Framework Convention on Climate Change (UNFCCC) emission accounting rules, whereas international emissions do not (they are estimated and reported but are not included in countries' total emissions or targets), and the Kyoto Protocol assigned the responsibility of international aviation emissions (sometimes referred to as emissions arising from international bunker fuels) to the International Civil Aviation Organization

[4] Total global CO_2 emissions arising from the combustion of fossil fuels, cement manufacturing and land-use change. See http://www.globalcarbonproject.org/ for an overview

[5] 1 Mt = 1 million tonnes = 1×10^9 kilogrammes or 1×10^{12} grams

[6] RPK is a measure of 'transport work', i.e. what is carried, in terms of people multiplied by total distance; ASK is a measure of capacity. Currently, passenger load factors are at around 85 – 90% (see data in footnote 8 below)

[7] A succinct summary of how global climate policy developed, resulting in the Paris Agreement is given by Gao et al. (2017)

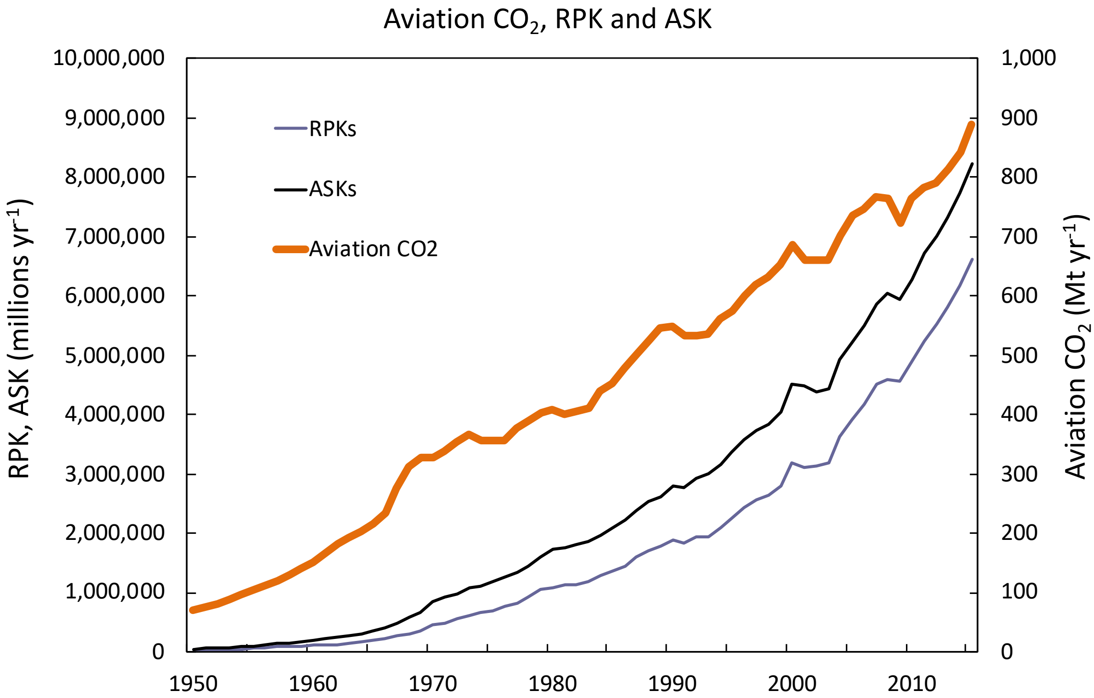


Figure 1. Growth in Available Seat Kilometres (ASK), Revenue Passenger Kilometres (RPK), shown on the left-hand axis, and CO_2 emissions from 1950 to 2015 in millions of tonnes (Mt) per year, shown on the right-hand axis. Data and chart updated from Lee et al. (2009) from A4A (traffic statistics[8]) and the International Energy Agency (IEA) for total aviation fuel usage.

The Paris Agreement's aim is: "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" (Article 2, 1a). To achieve these goals requires a declining overall emission rate of CO_2 over time, including negative emissions in the second half of the current century (see Figure 2). A typical set of possible 'emissions trajectories'[9] for avoidance of 2°C warming is shown in Figure 2.[10] As Figure 2 shows, in order to avoid 2°C of warming by 2100, negative emissions are required somewhere between 2050 – 2090. To avoid 1.5°C of warming, even more stringent emissions scenarios would be required, i.e. a lesser amount of emissions with zero and negative emissions at an earlier date (IPCC, 2018 – see Appendix 1 for an illustration).

Achievement of negative emissions (see section 5) is envisaged by a range of technologies that will remove CO_2 from the atmosphere in excess of potential bio-uptake by increased planting of e.g. forests (Smith et al., 2016; Kriegler et al., 2018).

The key defining metric in terms of not exceeding some temperature target is not the emissions rate of CO_2, i.e. the amount (mass) of emissions per year, but rather the *cumulative* (sum of) emissions over time (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfield et al., 2009; IPCC, 2013) since there is an approximately linear relationship between temperature and the cumulative CO_2 emitted.[11] This 'carbon budget' approach is being taken in monitoring progress towards the Paris Agreement Goals (e.g. UN Environment, 2017).

[8] http://airlines.org/dataset/world-airlines-traffic-and-capacity/
[9] Emission trajectories, or sometimes 'pathways' are the development over time of projected emissions.
[10] An equivalent comprehensive set of 1.5°C emission trajectories was not publicly available at the time of writing
[11] The cumulative emissions of CO_2 are what determines the CO_2 radiative forcing response and the ultimate temperature response. There is a large body of evidence that shows an approximately linear relationship

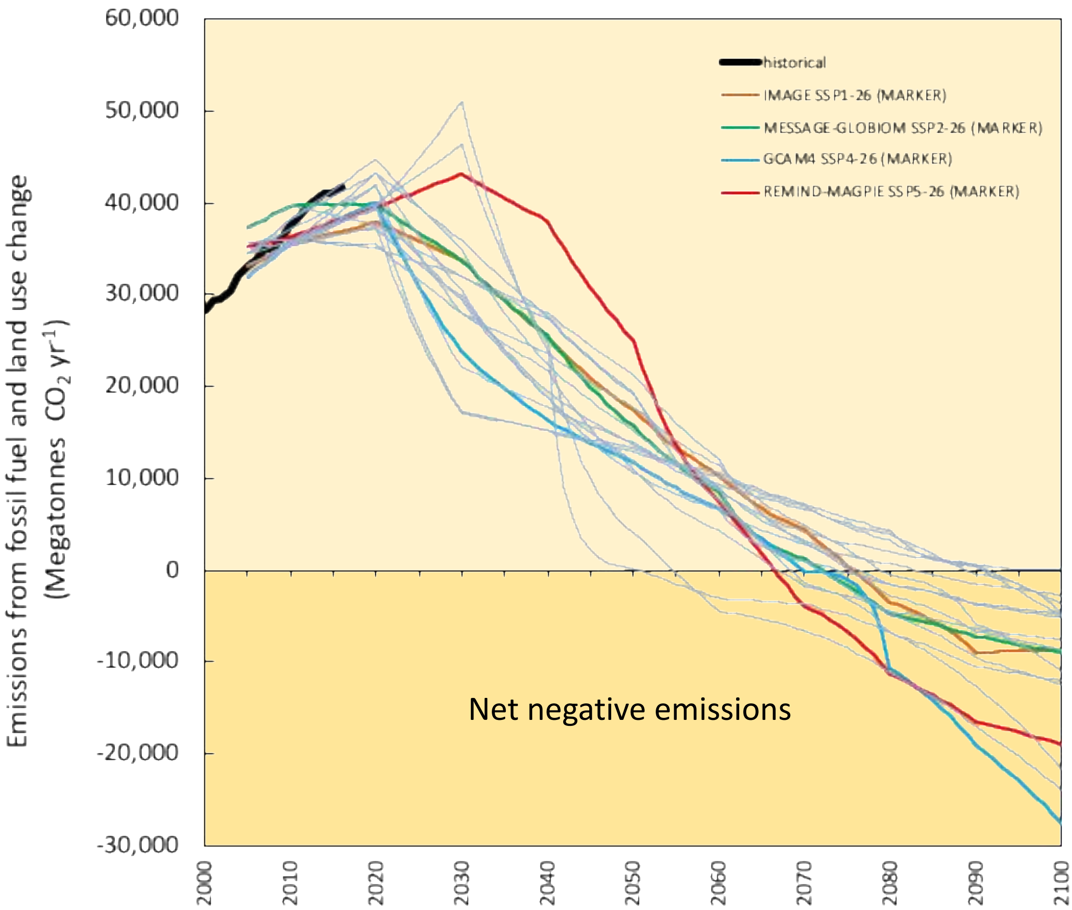


Figure 2. Shared Socioeconomic Pathways (IIASA SSP Database) scenarios of CO_2 emissions (Megatonnes CO_2 yr^{-1}) for 2.6 W m^{-2} forcing that avoids 2°C of warming by 2100. Representative marker scenarios are indicated by bold coloured lines and all other scenarios by light blue lines. Source: Riahi et al., 2016; IIASA SSP database.

Aviation still shows a strong dependency on liquid fossil fuels, given that sustainable biofuels are still not produced in large quantities or at a competitive price with fossil kerosene, with estimates of possibilities of biofuel usage in aviation in 2050 ranging from 10% ("Likely") to 30% ("Speculative") by the UK Committee on Climate Change (UKCCC, 2009). Schäfer (2016) points out that there are still long-term issues to be solved of scaling up production, infrastructure, and price competition with volatile conventional fossil-fuel based products. The UKCCC have recently re-examined potential future biofuel usage (UKCCC, 2018), including for aviation and recommended a goal of producing up to 10% of aviation fuel from biofuels with carbon capture and storage by 2050.

In the following sections we explore: what ICAO emissions projections show; the policies and measures 'in the pipeline' that will affect CO_2 emissions; what is implied by the non-CO_2 emissions from aviation; and whether aviation emission reductions will be consistent with the Paris Agreement.

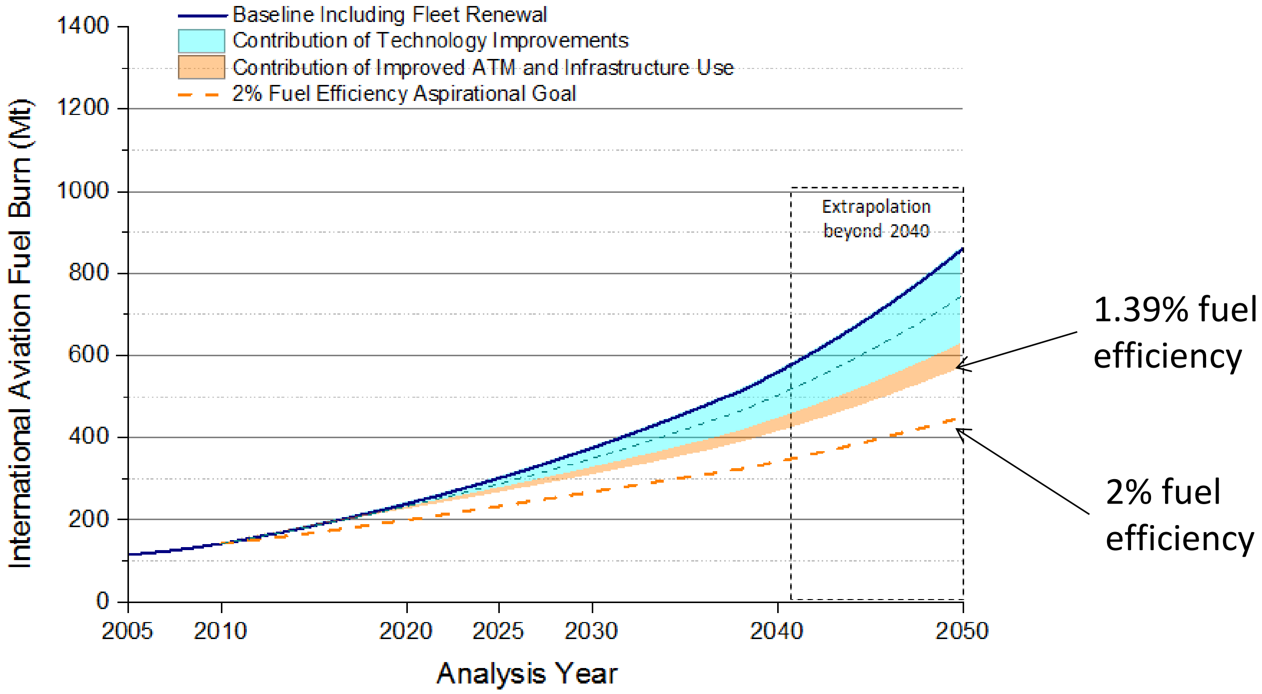
2 ICAO's long-term emissions projections

ICAO, within its Committee on Aviation Environmental Protection (CAEP), produces projections on both aviation traffic growth and technology trends developments that allow projections to be made of emissions of CO_2, nitrogen oxides (NO_x)[12] and particulate matter (PM) to 2050 (see Figure 3 for

between cumulative CO_2 and increases in global mean surface temperature changes. This was emphasised in the last Assessment Report of the IPCC (IPCC, 2013), which is why this metric is used here in the analyses presented, in order show simple but relevant calculations of aviation's projected share of CO_2 emissions

[12] NO_x = sum of nitric oxide (NO) + nitrogen dioxide (NO_2)

CO_2 projections). Projections of 'high', 'medium' and 'low' traffic growth and a range of technology development scenarios are combined, in order to produce emission projections. The latest aviation emission trends assessment by ICAO is available in its Environmental Review (ICAO, 2016) and is described in detail by Fleming and Ziegler (2016). However, ICAO only gives details of international aviation emission trends, rather than total sectoral, i.e. international plus domestic (although domestic global emissions are calculated). This is because ICAO's mandate is for international emissions only. Nevertheless, Fleming and Ziegler (2016) report that the international fraction of emissions was 65% in 2010, expected to grow to around 70% by 2050.



*Dashed line in technology contribution sliver represents the "Low Aircraft Technology Scenario."
Note: Results were modelled for 2005, 2006, 2010, 2020, 2025, 2030, and 2040 then extrapolated to 2050.

Figure 3. International usage of aviation fuel projected to 2040 and extrapolated to 2050 for ICAO-CAEP's mid-traffic growth projection, showing the potential contributions to fuel reductions over time from technology (light blue shaded area), improved air traffic management (ATM) and infrastructure (light brown shaded area) over a baseline scenario, and the ICAO aspirational goal of an overall fleet efficiency improvement of 2% per year (dashed orange line). Reproduced from Fleming and Ziegler (2016).

3 Existing ICAO policies and measures on aviation CO_2 emissions

Under the Kyoto Protocol, CO_2 was the only relevant emission from aviation in the 'basket' of greenhouse gases that the Protocol considered. Annex I Parties to the United Nations Framework Convention on Climate Change (UNFCCC) were required to work through ICAO to "limit or reduce" international aviation CO_2 emissions (Article 2.2 of the Kyoto Protocol). Domestic aviation CO_2 emissions formed part of Parties' national commitments.

The Paris Agreement does not explicitly refer to aviation emissions (international or domestic) although it is assumed that the responsibility for continued action on international emissions will remain with ICAO.[13]

[13] https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ6.aspx

ICAO Guidance and Goals. Existing measures on CO_2 within ICAO include guidance on operational opportunities to minimise fuel usage and reduce emissions. Further, ICAO adopted the following goals for aviation:

— a global annual average fuel efficiency improvement of 2% to 2050; and

— a collective medium-term global aspirational goal of keeping the global net carbon emissions from international aviation from 2020 at the same level (CNG2020).[14]

ICAO CO_2 Emissions Standard. In March 2017, the ICAO Council adopted an aircraft CO_2 emissions standard. The CO_2 standard will apply to new aircraft type designs from 2020 and to aircraft type designs already in-production as of 2023. Those in-production aircraft that do not meet the standard by 2028 will no longer be able to be produced unless their designs are sufficiently modified.

There is little information available on what the CO_2 Standard implies in terms of absolute emission reductions from the global fleet. ICAO did not define a 'baseline' or business-as-usual projection for the CO_2 Standard. However, one estimate puts the emissions saved as being "*more than 650 Million tonnes between 2020 and 2040*".[15] Because the CO_2 Standard was formulated independently of the range of technology projections shown in Figure 3, it is unclear where these savings from the CO_2 Standard lie, relative to the envelope of potential emission reductions envisaged shown in Figure 3.

The estimated scale of savings that will be achieved by the CO_2 Standard between 2020 and 2040 of 650 million tonnes may be compared with the *total* cumulative emissions from aviation[16] between the same dates of ~26 to 38 billion[17] tonnes CO_2 (representing a full span of traffic growth and technological/operational improvement scenarios, no CNG2020), i.e. the effect of the CO_2 standard would represent an additional 1.7% to 2.5% savings, if additionality of the CO_2 Standard is assumed.

ICAO's International Carbon Offsetting Measure. Lastly, ICAO has recently agreed a global market-based offsetting measure – the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).[18] CORSIA is the main means by which ICAO aims to achieve as close as possible to its CNG2020 goal and is the first internationally-agreed sectoral measure.

The impact of CNG2020 on international aviation CO_2 emissions to 2035 (the limit of the current formulation of CORSIA) is shown in Figure 4.

Impact of CNG2020 on international emissions

The aim of CNG2020 is to limit international aviation emissions of CO_2 to 2020 levels. This is to be achieved through carbon offsetting. In reality, aviation continues to emit increasing levels of CO_2 emissions as it grows as a sector, but the emissions are 'offset' through a purchasing system where other sectors or individual emitters reduce their emissions, relative to their baseline or status quo emissions.

With CNG2020, the cumulative emissions of aviation CO_2 between 2021 and 2035 for the full envelope of ICAO-CAEP's traffic growth and technology/operational improvement scenarios would be between 9.8 billion tonnes of CO_2 (low traffic growth, maximum technological and operational improvements – 'max tech') and 11.2 billion tonnes CO_2 (high traffic growth, minimum technological and operational improvements – 'min tech'), although the actual fossil fuel emissions would be between 12.2 and 16.9 billion tonnes of CO_2.

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[14] 'Carbon Neutral Growth goal, 2020'

[15] https://obamawhitehouse.archives.gov/the-press-office/2016/02/08/fact-sheet-us-leadership-securing-first-ever-global-carbon-emissions

[16] The CO_2 standard applies to airframes, regardless of domestic or international operation, so the saving estimate of 650 million tonnes between 2020 and 2040 applies to *total* aviation.

[17] 1 billion tonnes (1 Gt) = 1,000 million tonnes (Mt) i.e. 1×10^9 tonnes

[18] https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

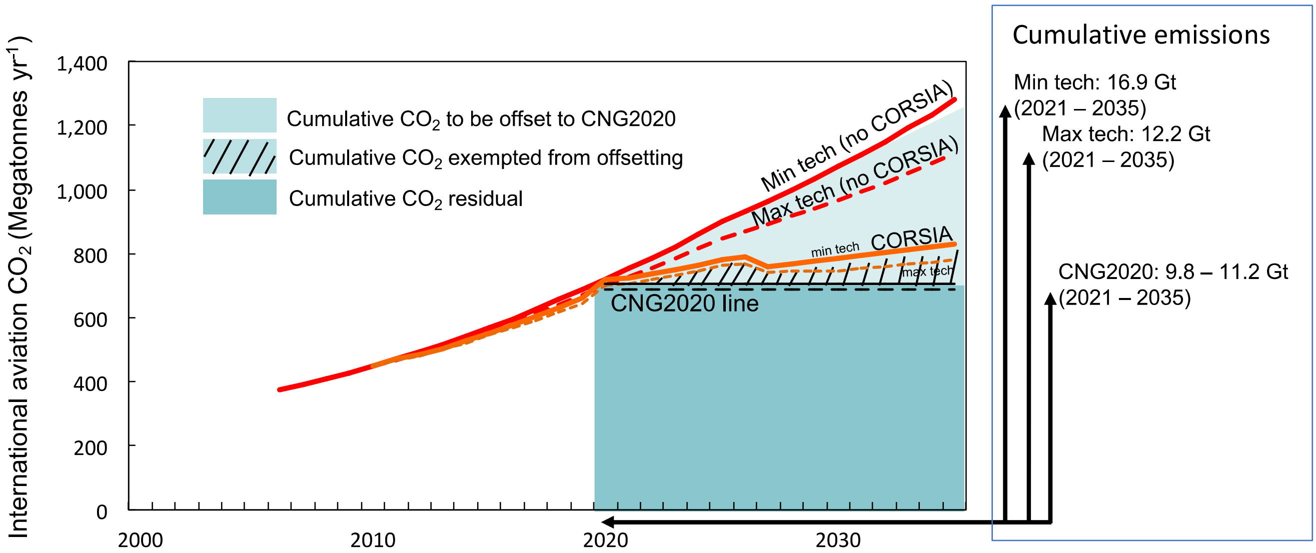

Figure 4. The projection of international aviation emissions of CO_2 from 2005 to 2035, showing growth offset over CNG2020 and exempted emissions under CORSIA for a central traffic growth scenario. The solid red line shows a 'min tech' development scenario and the dashed red line a 'max tech' scenario, and emissions under a hypothetical full compliance with CNG2020 goal (solid and dashed black horizontal lines – min, max tech). The darker blue area shows the residual emissions not offset (70% – 75% of the total between 2021 and 2035) and the lighter blue area above, to 'min tech'/'max tech', represents the emissions ideally offset under CORSIA (25% – 30% of the total between 2021 and 2035). The hatched area under the orange/orange dashed lines (min, max tech reductions with CORSIA) shows the emissions exempted under CORSIA, resulting in a ~78% environmental integrity of the scheme (Lee and Owen, 2016)[19]

4 How do ICAO's goals fit within temperature scenarios of less than 2°C by 2100?

Future generalized scenarios of greenhouse gas emissions have previously been formulated within the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2000) or by the broader international scientific community, within the context of IPCC analyses. The 'Representative Concentration Pathways' (RCPs) scenarios (Moss et al., 2010) were used extensively in analyses by the climate science community and the IPCC for its Fifth Assessment Report (IPCC, 2013). Since then, these have been superseded by the 'Shared Socioeconomic Pathways' (SSPs) (Riahi et al., 2016).

There are 5 SSP scenarios (SSP1–SSP5), which have broad narratives of different global policies, population and economic development, formulated to explore challenges to climate mitigation and adaptation. SSP1 represents "*Sustainability*"; SSP2 "*Middle of the Road"*; SSP3 "*Regional Rivalry*"; SSP4 "*Inequality*"; SSP5 "*Rapid Growth*". These SSPs have nominal global radiative forcing[20] levels by 2100 of 2.6 W m^{-2}, 4.5 W m^{-2}, and 6.0 W m^{-2} associated with them in order to retain consistency with the basis of the previous RCP scenarios, with an additional mitigation target of 3.4 W m^{-2} being included (Riahi et al., 2016). Very recently, the SSPs have been further updated to more stringent global radiative forcing levels of 1.9 W m^{-2} by 2100, which is in line with 1.5°C scenarios (Rogelj et al., 2018),[21] which were used in the recent Special Report of the IPCC on Global Warming of 1.5°C (IPCC, 2018).

[19] These calculations were made by MMU for The UNFCCC Conference of Parties 22nd meeting, Marrakech (16th November, 2016), and were based on the list available at the time of participating countries, which implied 78% of the required offsetting to achieve CNG2020, which is not dissimilar to that at the time of writing (August, 2018)

[20] For an explanation of radiative forcing, see companion note, Lee (2018): essentially, greater levels of radiative forcing by 2100 result in higher temperatures by 2100

[21] These were not publicly available at the time of writing for analysis

For the analysis presented here, the SSP scenario data have been extracted from the IIASA hosting website[22] for the 'marker' scenarios (as recommended by IIASA) for SSP1, 2, 4 and 5 for 2.6 W m^{-2} radiative forcing scenarios (there is no 2.6 W m^{-2} scenario for SSP3). The forcing level of 2.6 W m^{-2} was used as it produces temperature responses that are below a 2°C increase by 2100 for the marker scenarios, requiring strong mitigation measures such that negative emissions are required in the second half of the century. Data on global total CO_2 emissions and the corresponding temperature pathways were extracted and used.[23]

These emission and temperature pathway data for SSP1, SSP2, SSP4 and SSP5 are shown for the 2.6 W m^{-2} radiative forcing level[24] in Figure 5 in the context of total global aviation and international aviation emission projections to 2050 from ICAO.

In order to provide a simplified and comprehensive analysis, two extremes of the aviation scenarios were chosen, using the 'max tech' assumptions coupled with a low traffic growth projection (i.e. minimum emissions), and 'min tech' assumptions coupled with a high traffic growth scenario (maximum emissions).

A comparison between total and international aviation CO_2 emissions and total global CO_2 emissions was made by calculating the cumulative CO_2 from aviation (total and international) from 2016 to 2050 as fractions of total cumulative global CO_2 emissions from 2016 to 2100. This calculation represents the "share" that aviation emissions to 2050 are projected to have of the total cumulative CO_2 emissions budget to 2100 if the <2°C temperature goal is to be achieved.

Under the above assumptions, aviation's sectoral share between 2016 and 2050 of the total global cumulative CO_2, is projected to be somewhere between 4.3% and 14.8% of the total cumulative CO_2 budget available (2016 – 2100).

Similarly, but examining (cumulative) international aviation CO_2 emissions only, these are projected to be somewhere between 3.0% and 10.1% of the total cumulative CO_2 budget available (2016 – 2100).

For reference, aviation's share of total cumulative global CO_2 emissions from 1940 to 2016 was 1.4% (using data from Lee et al., 2009; Sausen and Schumann, 2000; Le Quéré et al., 2017; International Energy Agency).

Unlike the Kyoto Protocol, the Paris Agreement does not refer to specific greenhouse gases (GHGs) but rather, Article 4 (1) points to the need *"…to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…"*. This "balance" of GHGs is subject to some interpretation (Fuglestvedt et al., 2018), particularly in terms of the roles of long-lived GHGs and short-lived climate forcers (e.g. methane, ozone, aerosols, etc.).

The main GHG emitted from international aviation is CO_2; however, there are significant non-CO_2 climate forcings arising from emissions of particles, NO_x, and water vapour, including the formation of contrails and contrail-cirrus that give rise to additional warming over CO_2 (IPCC, 1999). Substantial mitigation opportunities may exist for these non-CO_2 forcings. However, the uncertainties on non-CO_2 forcings are greater than that for CO_2 forcing (see accompanying note, Lee, 2018).

[22] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

[23] Just the CO_2 data were extracted to allow a straightforward comparison with aviation emissions of CO_2. Other greenhouse gases such as nitrous oxide and methane etc. contribute towards the calculated temperatures but were not utilized

[24] 2.6 W m^{-2} equates to temperature levels of just less than 2°C by 2100 (see Figure 5)

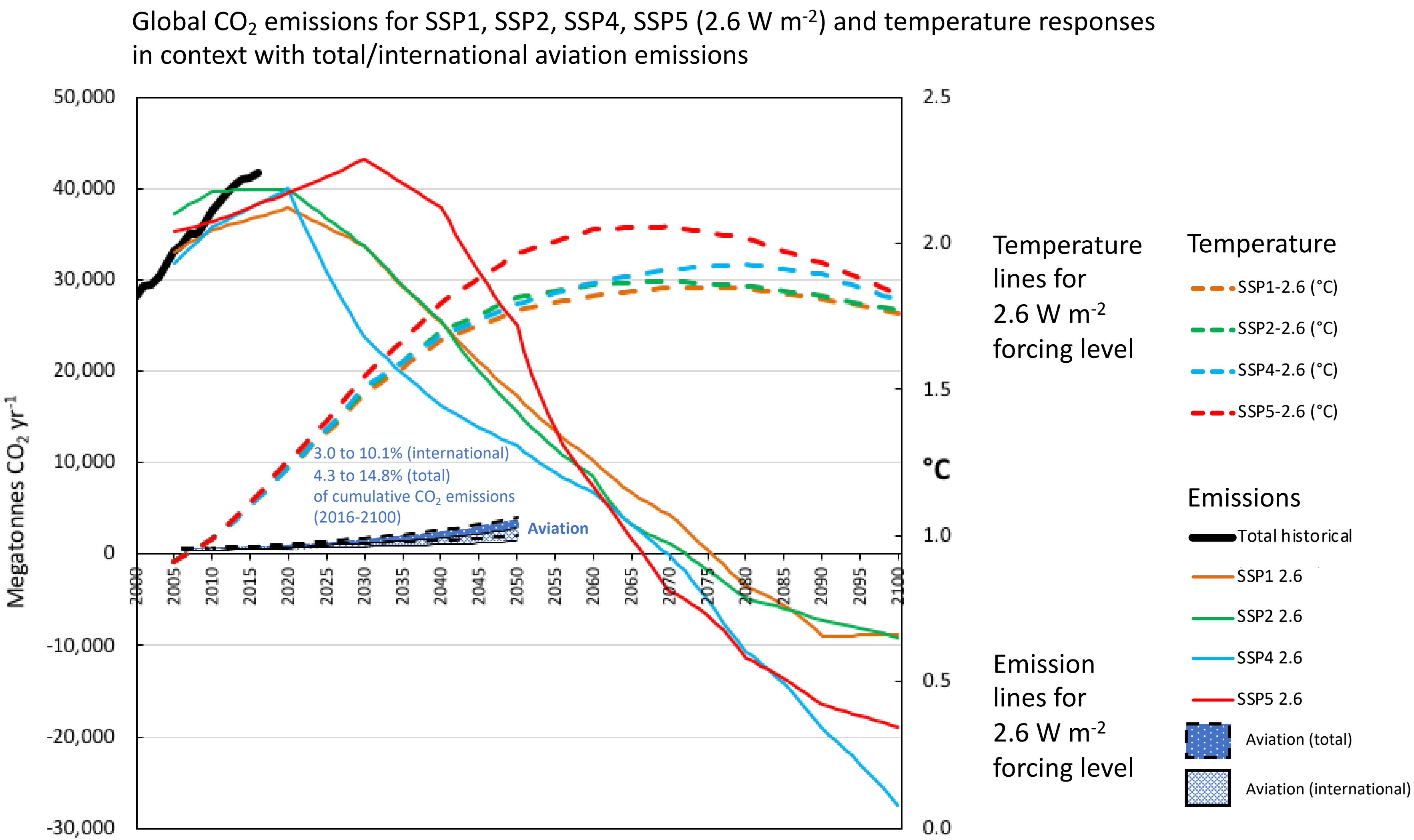

Figure 5. SSP1, SSP2, SSP4, SSP5 marker scenario emissions pathways and corresponding temperature responses for total global CO_2 emissions that result in temperatures of < 2°C by 2100 (forcing of 2.6 W m^{-2}), also showing total and international aviation emissions in a "minimum to maximum" envelope of emissions to 2050. Also shown are the total historical emissions of CO_2 (thick black line) from 2000 to 2016. Data from Riahi et al. (2016); Fleming and Ziegler (2016), IIASA SSP website, Le Quéré et al. (2017), Global Carbon Project.

Formulating CO_2 emission-equivalences (CO_2-*e*) for short-lived climate forcers such as aviation's non-CO_2 emissions and effects is problematic, with a range of emission-equivalence metrics being available, the most commonly used being the Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) (Shine et al., 2005). Both metrics have arguments for and against, and both require a choice of time horizon (the length of time over which the metric is calculated). Under the Kyoto Protocol, the GWP for 100 years was used to calculate emission equivalences of non-CO_2 gases.

Using radiative forcing calculations presented by Lee et al. (2009) and the methods of Fuglestvedt et al. (2010), Lee et al. (2010) calculated composite GWPs and GTPs for aviation non-CO_2 effects, of 2 and 1.1 (i.e. multiplying CO_2 emissions by these factors), respectively for a 100 year time horizon.[25] If these metrics were used, this would give a cumulative CO_2-*e* emission fraction of total CO_2 emissions (2.6 W m^{-2} scenarios) for aviation of 8.7% – 29.6% under a GWP100 assumption. For the GTP100 metric, these fractions would be: 4.8% – 16.3%.

This aspect of accounting for aviation non-CO_2 short-lived climate forcers becomes important as one approaches the 'target' temperature, since by their nature such forcings only have a short-term impact whereas CO_2, being long-lived needs to be considered long before any critical temperature threshold. More recently, emission equivalence metrics have been proposed by Allen et al. (2016; 2018) that may be more suitable for short-lived climate forcers but have not, as yet, been applied to aviation forcings.

It is important to note that the Paris Agreement seeks to limit temperature increases to "…*well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels."* The 'SSPx-1.9' (W m^{-2}) scenarios for 1.5°C (Rogelj et al., 2018) were not available at the time of analysis. Thus, for more ambitious temperature targets, the current share of emissions estimated to be taken by aviation will be larger than those presented here.

5 Timescales and the role of negative emissions technologies in aviation development

The CORSIA mitigation strategy for growth in international aviation emissions of CO_2 relies on 'offsetting'. There are two issues associated with offsetting in the near and long term that need to be understood:

- offsetting from reforestation and afforestation has a built-in time delay of years to decades;
- over-reliance on future 'negative emissions technologies' (NETs) needs to be avoided when considering the future growth of aviation.

The timing aspect of offsetting from reforestation/afforestation

Planting trees (primarily) might seem to be a reasonable, effective, and relatively inexpensive means of offsetting CO_2 emissions (NAS, 2015). However, the carbon uptake as a result of the difference between photosynthesis and respiration (i.e. growth) does not occur instantaneously. Carbon uptake by vegetation planting is critically dependent upon location, vegetation type/species, and local environmental factors. Moreover, if the soil is disturbed in the process of planting and CO_2 emissions result, the process is in CO_2 *deficit* until sufficient carbon uptake has occurred which may be on the timescale of years to decades (EASAC, 2018). Assuming reforestation, depending upon location, environmental factors and species, the maximal carbon uptake may occur between 20 and 60 years after planting, and thereafter the rate of uptake declines (EASAC, 2017; 2018). Thus, the 'offset' does not occur straight away but over a timescale of decades – moreover, the long-term carbon sink of reforestation only occurs with careful forest maintenance and management, with a commitment to the long term.

[25] See accompanying note, Lee (2018) for a full explanation of GWP, GTP

It is clear from the 2°C emissions pathways illustrated here, and from the recent IPCC Special Report of 1.5°C warming (IPCC, 2018) that CO_2 emissions need to decline from around 2020 to zero emissions around 2075 for 2°C emissions pathways or around 2050 for 1.5°C emissions pathways (see Appendix 1). Hence, carbon reductions that have a 'lag' built into them need to be accounted for in mitigation pathways, as they may contribute to temperature 'overshoot'.

Reforestation/afforestation and Negative Emissions Technologies

In order to realise the Paris Agreement goals of limiting a rise in global mean surface temperature of no more than 2°C and pursuing efforts to limit this to 1.5°C, the emissions pathways shown in Figures 2 and 5 (for 2°C pathways) indicate CO_2 emissions declining to zero and going negative at some point in the second half of the present century, or earlier for 1.5°C scenarios (see Appendix 1).

These emissions pathways have generally been developed from 'Integrated Assessment Models', which model energy, population, resources and emissions under various assumptions.[26] Integrated Assessment Modelling activities have come in for some criticism in their treatment of the implementation of Negative Emissions Technologies (NETs) (Anderson and Peters, 2016; EASAC, 2018) in that they do not always give sufficient detail or analysis of the plausibility of the NETs and the depths of the emissions cuts required (see BOX 1 for an overview of NETs).

The reason that NETs and their limitations are discussed briefly here is that one potential approach to aviation as a 'hard-to-decarbonize' sector, might be to accept that the sector needs to continue burning fossil fuels past, e.g. 2050, but that NETs would be utilized to compensate for these emissions. However, it is clear that ensuring negative emissions is difficult and uncertain: NETs need wide-scale and rapid deployment and thorough assessments of their near-term capacity (e.g. EASAC, 2018) show serious limitations, such that 'adding' to the burden of NETs to remove the necessary CO_2 from the atmosphere by accepting an increasing fossil fuel burden from aviation runs risks that could be difficult to mitigate at a later date, should NETs not have sufficient or reliable capacity.

BOX 1 Negative Emissions Technologies (NETs)

Negative emissions technologies currently envisaged can be grouped as follows:

- Afforestation and reforestation;
- Land management to increase carbon fixation in soils;
- Bioenergy production with carbon capture and storage (BECCS);
- Enhanced weathering;
- Direct capture of CO_2 from the air;
- Ocean fertilization to increase CO_2 uptake.

Efforts have been made to provide assessments of the magnitude and constraints of these technologies (e.g. EUSAC, 2018; UN Environment, 2017; Smith et al., 2016), to which the reader is referred. However, NETS cannot, as yet, be seen as a panacea to climate change and successful constraint of global mean surface temperatures, even if global CO_2 emissions peak shortly and rapidly decline through mitigation efforts (Anderson and Peters, 2016). The US National Academy of Sciences (NAS, 2015) summarizes this as:

"*The barriers to deployment of CDR* [Carbon Dioxide Removal] *approaches are largely related to slow implementation, limited capacity, policy considerations, and high costs of presently available technologies.*"

The European Academies Science Advisory Council (EASAC, 2018) similarly conclude:

"*Having reviewed the scientific evidence on several possible options for CO_2 removal (CDR) using negative emission technologies (NETs), we conclude that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios (as much as several giga tonnes (one billion or 10^9 tonnes) of carbon each year post-2050).*"

The 2017 UN Environment 'Bridging the emissions gap' report (UN Environment, 2017), presents a more positive view:

"*Carbon dioxide removal from the atmosphere can provide an additional mitigation element to conventional emission abatement strategies. Biological CO_2 removal through afforestation, reforestation, forest management, restoration of degraded lands, soil carbon enhancement and biochar application in agriculture can play an immediate role, and can also significantly contribute to achieving several other Sustainable Development Goals.*"

but is nonetheless cautious about the limitations of the engineering approaches within NETs.

[26] See http://sedac.ciesin.columbia.edu/mva/iamcc.tg/mva-questions.html for an overview

6 Is ICAO's CNG2020 goal consistent with the temperature goals of the Paris Agreement?

Clearly, if international aviation CO_2 emissions from fossil fuel continue at 2020 levels to the point at which zero global CO_2 emissions will be required (around 2075 for the 2°C scenarios, as shown in Figure 5, and 2050 in 1.5°C scenarios, Appendix 1), then this will be inconsistent with the Paris Agreement's goals. This is because global emissions of CO_2 must fall dramatically after 2020 to zero and then CO_2 removal from the atmosphere will be required. Any continued usage of fossil fuel for aviation past the point at which zero then negative emissions are required would imply more CO_2 removal from negative emissions technologies than currently envisaged.

Achievement of the Paris Agreement Goals are anticipated to be difficult. Currently, the Nationally Determined Contributions (NDCs) are insufficient, according to the most recent available analysis by UN Environment (UN Environment, 2017) who conclude that "*The gap between the reductions needed and the national pledges made in Paris is alarmingly high.*" The UN Environment (2017) analysis indicates that if the current NDCs are fully implemented, the carbon budget for holding warming well below 2°C will be about 80% depleted by 2030 and "*well depleted*" for a 1.5°C target. Total global emissions of CO_2 urgently need to be reduced and there is a significant 'gap' between required emission reductions and those projected from the NDCs (UN Environment, 2017). Aviation is a sector that is widely recognized to be difficult to decarbonize because of its high dependence on liquid fossil fuels, so achieving a 1.5°C target will become irreconcilable with any continued fossil fuel usage by aviation at some point around the middle of the present century in the absence of further measures. [27]

In addition, there is a further potential complication in that the Paris Agreement is a *temperature-based* target that does not specify specific greenhouse gases (GHGs), in contrast to the former Kyoto Protocol, which defined a 'basket' of particular GHGs. This temperature basis of the Agreement would imply that *all* emissions and impacts that affect global mean surface temperatures fall under the Paris Agreement. Aviation has a number of non-CO_2 impacts that significantly increase its contribution to warming over and above that from its CO_2 emissions (see accompanying note, Lee, 2018).

Solving this apparent inconsistency of continued long-term aviation CO_2 emissions from fossil fuels with the goals of the Paris Agreement requires actions that are political, technological and regulatory. Independent assessments of the current and projected status of NETs imply that NETs cannot necessarily be relied on to offset continued usage of fossil fuel by the aviation sector beyond 2050. Since aviation's current goals are inconsistent with the Paris Agreement, in the absence of additional measures, then more ambitious goals should be set.

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[27] The IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) became available only in the finalization stages of writing this report and as noted earlier, the emissions data for 1.5°C emission trajectories were not publicly available. However, in support of this statement, the illustration of emission trajectories was added late in the production process of this report in Appendix 1 in order to illustrate the scale of the problem.

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Appendix 1

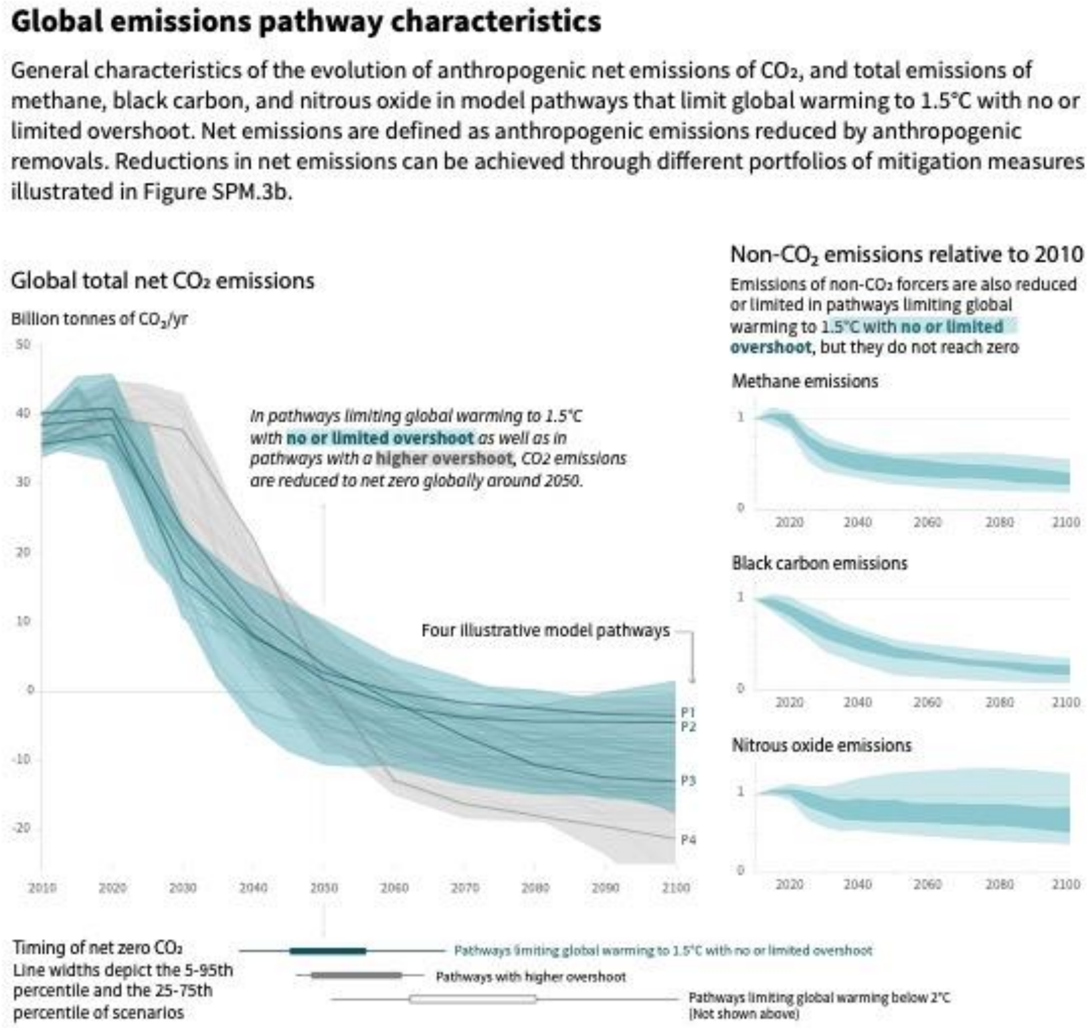

Figure SPM.3a: Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

The above figure is reproduced with its legend in entirety from the Summary for Policymakers from IPCC (2018). The left-hand figure of 'Global total net CO_2 emissions' may be compared with Figure 5 of this document, in terms of where potential aviation emissions projected to 2050 may lie, showing that there is a 'clash' of required zero CO_2 emissions, within a certain time bandwidth depending on the particular 1.5°C pathway.